

# Remarks on the possible importance of jet $v_3$ and multiple jet production for the interpretation of recent jet quenching measurements at the LHC

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Recent jet quenching measurements in Pb+Pb collisions at the LHC report a significant energy imbalance of di-jets. The imbalance is found to be compensated by a large amount of soft particles produced at large angles with respect to the di-jet axis. This observation questions the conventional picture of parton energy loss models, established at RHIC, which typically expect that the radiated gluons are emitted at moderate angles close to the outgoing parton. In this letter, we qualitatively discuss two possible contributions of the underlying heavy-ion background that may have to be taken into account when interpreting the recent data. We show that a large jet  $v_3$ , potentially caused by a pathlength dependent energy loss in the presence of fluctuating initial conditions, could contribute to the observed excess of soft particles apparently originating from large angle in-medium radiation. In addition, the observed excess could also be induced by multiple jets produced in the vicinity of the leading jet, caused by a potential selection bias imposed on the di-jet momentum imbalance.

## I. INTRODUCTION

One of the most important discoveries in the collision of heavy nuclei at the Relativistic Heavy Ion Collider (RHIC) is the observation that the inclusive yield of high transverse momentum ( $p_T$ ) hadrons [1, 2] and the semi-inclusive rate of azimuthally back-to-back high- $p_T$  hadron pairs are strongly suppressed relative to the expected yields in p+p and d+Au collisions [3–5]. Since high- $p_T$  particles are dominantly produced in the fragmentation of QCD jets, the effect has been called “jet quenching”, expressing the expectation that the parton loses energy in the interaction with soft gluons of the medium created in the heavy-ion collisions.

Two different mechanisms have been proposed to describe parton production and evolution in the case of a medium: (a) collisional energy loss due to elastic scatterings [6, 7], and (b) energy loss due medium-induced gluon radiation [8–10]. Most quantitative attempts to model the jet quenching data from RHIC rely on the radiative energy loss scenario as the main dynamical mechanism responsible for the energy loss [11].

However, as the measurements at RHIC mainly address medium effects concerning the most energetic (leading) particle in the jet, the predictions of these models have not really been tested until recently, when the first measurements of fully reconstructed di-jets in Pb+Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV at the Large Hadron Collider (LHC) have been reported [12, 13]. These measurements show a strong increase in the fraction of highly momentum-imbalanced di-jets in central as compared to peripheral collisions. Furthermore, a large fraction of the momentum imbalance is found to be carried by a large amount of low- $p_T$  ( $\lesssim 4\text{GeV}/c$ ) particles at large angles ( $> 45^\circ$ ) with respect the jet axis [13]. Whereas the hard component of the momentum distribution of jet constituents reconstructed in Pb+Pb collisions is found

to be remarkably similar to jets of the same reconstructed energy fragmenting in the absence of a medium [14].

These observations are difficult to reconcile with most radiative energy loss models, established at RHIC, in which the radiated gluons are typically emitted at only moderate angles close to the outgoing parton, leading to a characteristic modification of the jet internal structure [15, 16]. The new data from the LHC, qualitatively predicted by [17, 18], have prompted the development of more sophisticated models [19–29] to quantitatively describe the di-jet energy imbalance. It also has been pointed out [30] that, depending on the applied correction scheme, residual contributions of the underlying, soft heavy-ion background and its fluctuations can artificially enhance the observed energy imbalance.

In this letter, we discuss the reported excess of soft particles outside of the leading jet cone of  $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.8$ . On the qualitative level we address two possible contributions of the heavy-ion background that may affect the current interpretation of the out-of-cone radiation. The first contribution arises from a potential jet  $v_3$ , which could be caused by a pathlength dependent energy loss in the presence of fluctuating initial conditions [31]. In Section II we show that under the assumption of a large jet  $v_3$  the observed excess of soft particles at large angles can be artificially enhanced. The second contribution arises from multiple, independent, partially overlapping di-jets in the heavy-ion event. In Section III, for simplicity, we discuss the probability for a second independent lower-momentum di-jet pair produced such that one jet is close to the leading jet, while its partner lies outside of the cone. Finally, in Section III and Section IV we briefly discuss the interplay between the mentioned effects, and the observed di-jet energy imbalance  $A_J$ .

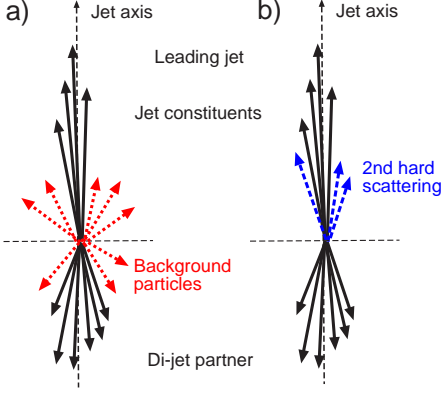


FIG. 1: (Color online) Illustration of the in-cone composition of the particle momentum distribution relative to the jet axis of particles originating from the di-jet and a) from the  $v_3$  background b) from a second hard scattering overlapping with the leading jet, but not with the di-jet partner.

## II. JET $v_3$

In this section, we qualitatively study the effect of a finite jet  $v_3$ , on the missing momentum ( $p_T^{\parallel}$ ) observable introduced in Ref. [13]

$$p_T^{\parallel} = - \sum p_{T,i} \cos(\phi_i - \phi_J), \quad (1)$$

with  $\phi_i$  the azimuthal angle of all charged tracks within a certain  $p_T$  range and  $\phi_J$  the azimuthal angle of the leading jet. For details concerning jet reconstruction, detector acceptance and kinematical cuts we refer to Ref. [13].

In Fig. 1 a), we illustrate the composition of the particle momentum distribution relative to the jet axis of particles originating from the di-jet and from the expected  $v_3$  background in case of a finite jet  $v_3$ . The main point to note is that the particle distribution caused by  $v_3$  is not symmetric around zero and  $\pi$ , as we will outline below.

For convenience, one can express the  $p_T^{\parallel}$  observable as an effective two-particle correlation using  $\Delta\phi = \phi_i - \phi_J$

$$p_T^{\parallel} = -A \int_{p_T^{\min}}^{p_T^{\max}} dp_T p_T dN/dp_T \int_{\Delta\phi^{\min}}^{\Delta\phi^{\max}} d\Delta\phi \left(1 + 2 \sum V_{n\Delta}(p_T) \cos(n\Delta\phi)\right) \cos(\Delta\phi), \quad (2)$$

with  $V_{n\Delta}$  denoting the product of the jet and particle  $n^{\text{th}}$  order harmonic,  $V_{n\Delta} = v_n v_n^{\text{Jet}}$  and  $p_T dN/dp_T$  the transverse momentum for a given kinematic selection of the charged particles in  $[p_T^{\min}, p_T^{\max}]$ . Since the single particle harmonics are found to be only weakly dependent on  $\eta$  [32], we assume the same for  $v_n^{\text{Jet}}$ , and so the integration over  $\Delta\eta$  has been absorbed into an overall normalization factor  $A$  for the geometrical detector acceptance.

Integration over the full  $\Delta\phi$  phase-space ( $\Delta\phi^{\min} = -\pi$  and  $\Delta\phi^{\max} = \pi$ ) for all  $p_T$  results in  $p_T^{\parallel}$  identical to zero

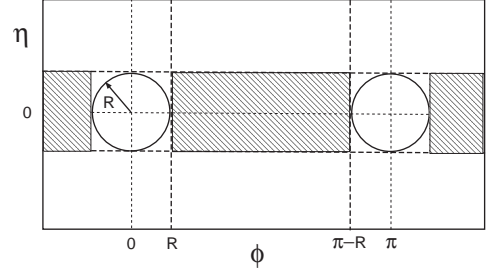


FIG. 2: Simplistic presentation of the considered phase space for Eq. 3.  $R$  is the radius defining the in- and out-of-cone region as used in Ref. [13].

for all harmonics, indicating that the soft, flow modulated background does not contribute to the  $p_T^{\parallel}$  measurement, as also suggested by the data [13]. This feature makes the  $2\pi$ -integrated  $p_T^{\parallel}$  observable a powerful tool to study jet-quenching effects in heavy-ion collisions.

However, this changes if one considers in- vs. out-of-cone contributions to  $p_T^{\parallel}$  separately from particles in- or outside of the jet cone of radius  $R$ . In Fig. 2 we illustrate the phase space region we use in our simplified, but analytical, approach to mimic the exclusion of particles in a jet cone of  $R$  ( $\Delta\phi^{\min} = R$  and  $\Delta\phi^{\max} = \pi - R$ ). Since for the  $p_T^{\parallel}$  studies the jet selection in Ref. [13] has been tightened requiring the di-jet partner to be at  $\Delta\phi > 5/6\pi$  on the away-side, and since we assume no  $\eta$  dependence of  $V_{n\Delta}$ , we can choose the di-jets to be located at ( $\eta = 0, \phi = 0$ ) and ( $\eta = 0, \phi = \pi$ ). Using Eq. 2 to estimate a lower limit on the out-of-cone contribution  $p_T^{\parallel, \text{out}}$ , we find that odd harmonics do not cancel in  $p_T^{\parallel, \text{out}}$ , while the even harmonics do.

In the following, we consider only  $v_3$  as the expected dominant contribution to  $p_T^{\parallel, \text{out}}$

$$p_T^{\parallel, \text{out}} = -4R \int_{p_T^{\min}}^{p_T^{\max}} dp_T p_T dN/dp_T \int_R^{\pi-R} d\Delta\phi (1 + 2V_{3\Delta}(p_T) \cos(3\Delta\phi)) \cos(\Delta\phi). \quad (3)$$

The missing momentum for particles out-of-cone has to be balanced by the missing momentum for particles in the cone. Thus, the fact that the 3<sup>rd</sup> harmonic is not symmetric around zero and  $\pi$ , leads to an increase of soft background particles in the direction of the leading and consequently to a decrease of soft background particles in the direction of the di-jet partner (see Fig. 1). This asymmetry results in a decrease of  $p_T^{\parallel}$  for soft particles in the direction of the leading jet even if the soft quenched particles are fully contained inside the jet cone. As a consequence this will then result in an enhanced low- $p_T$  contribution in  $p_T^{\parallel, \text{out}}$  in the direction of the di-jet partner.

In Fig. 3 (top panel) we show  $p_T^{\parallel, \text{out}}$  as function of  $V_{3\Delta}$  for three different selections of  $p_T$  for charged particles

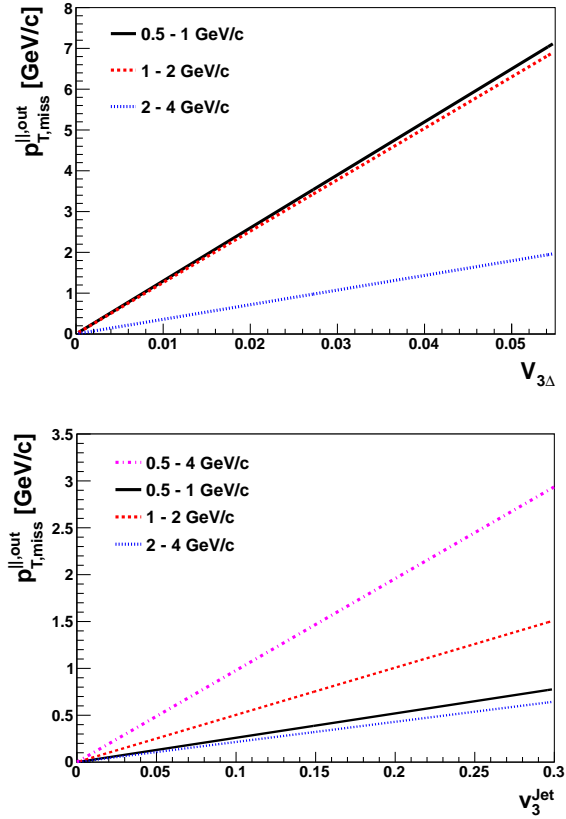


FIG. 3: (Color online) Missing transverse momentum  $p_{T,miss}^{||,out}$  (see Eq. 3) as function of  $V_{3\Delta}$  (top) and  $v_3^{Jet}$  assuming bulk  $v_3$  values from [33] (bottom) for three choices of particle  $p_T$  using event multiplicities and transverse momentum spectral shapes for 0–30% central Pb+Pb collisions.

with event multiplicities and transverse momentum spectral shapes for 0–30% central Pb+Pb collisions [34, 35]. The jet  $v_3^{Jet}$  is unknown, but could be substantial in a path-length dependent energy loss picture, and so a finite contribution to  $p_{T,miss}^{||,out}$  is expected. Since  $V_{3\Delta} = v_3 v_3^{Jet}$  one can use the measured bulk  $v_3$  values [33] and with assumptions concerning jet  $v_3^{Jet}$ , one can estimate the possible contributions to  $p_{T,miss}^{||,out}$  as illustrated in Fig. 3 (bottom panel). For example, assuming a  $v_3^{Jet} = 0.2$  the  $p_T$  integrated (0.5–4 GeV/c) contribution to  $p_{T,miss}^{||,out}$  can be up to 2 GeV/c.

### III. MULTIPLE JET PRODUCTION

In this section, we qualitatively discuss the effects of multiple jet production. The effect of 3-jet events on  $A_J$  and  $p_{T,miss}^{||}$ , where the third jet is outside of the cone, is already taken into account in the p+p reference in Ref. [13], estimated using the Pythia Monte Carlo generator. We further compute the 3-jet event probability using NLOJet++ [36]. For similar kinematic requirements as

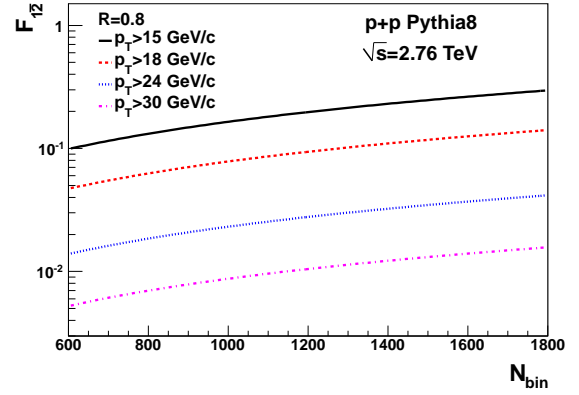


FIG. 4: (Color online) Fraction of di-jet events as function of  $N_{bin}$ , in which a second hard-scattering overlaps with the leading jet (matching criteria  $< R/2$ ) for different values of minimum  $\hat{p}_T$ .

in [13], we find the fraction to be less than 10%. (Estimates kindly provided by the authors of [25] suggest an even smaller contribution.) Since 3-jet events are already present in p+p collisions and since we discuss modifications with respect to the p+p reference, 3-jet events can therefore not be the only explanation of the observed increased di-jet imbalance, nor of the  $p_{T,miss}^{||}$  measurements.

In heavy-ion collisions, however, one expects the cross section for hard processes to scale with the number of independent nucleon–nucleon collisions. Therefore, with respect to a selected di-jet there potentially are up to  $\langle N_{bin} \rangle - 1$  independent additional hard-scatterings above a certain  $p_T$  per event, which all should be treated as background. Thus, one can imagine cases where one of the  $n^{th}$  hard scatter overlaps with the selected leading jet, see Fig. 1 b), but its di-jet partner lies outside of the cone of the selected di-jet system.

Since no background subtraction was performed in the  $p_{T,miss}^{||}$  in- and out-of-cone distributions and from the  $2\pi$  integrated distribution we know that on average, given the kinematic selection and acceptance, the  $n^{th}$  hard scattering balance, one has to estimate the fraction of events where an additional jet overlaps in  $R < 0.8$  with the leading jet, but not on the recoil side. For simplicity, we estimate the fraction of 2<sup>nd</sup> hard scatterings,  $F_{12}$  above a certain  $\hat{p}_T$  threshold using Pythia8 [37] at  $\sqrt{s} = 2.76$  TeV with a matching/overlap criteria of  $R/2$ . In Fig. 4, the fraction for several  $\hat{p}_T$  selections as a function of  $N_{bin}$  is shown. According to our simplistic estimate, the probability of a 2<sup>nd</sup> hard scattering is about 8% for  $\hat{p}_T > 18$  GeV/c at  $\langle N_{bin} \rangle \approx 1000$  (corresponding to 0–30% central collisions) to be in the vicinity of the leading jet and outside the recoil cone. By symmetry, the probability of having the second hard scattering close to the di-jet partner is equally probable and hence, on average, the two cases should cancel. However, for larger  $A_J$ , as discussed in the next section, one can imagine a stronger,

centrality dependent, bias towards events, in which a 2<sup>nd</sup> hard jet is in the vicinity of the selected leading jet. In addition, due to the hard cutoff imposed on the leading jet energy ( $> 120$  GeV/c in [13]) the fraction of these events should be enhanced due to a feed-up of lower energetic jets in the measured di-jet selection.

In case the 2<sup>nd</sup> hard jets are quenched, but not fully thermalized, they would contribute to the apparent imbalance of the  $p_T^{\parallel}$  in-cone, especially at lower  $p_T$  and consequently to an enhancement in the  $p_T^{\parallel}$  out-of-cone at lower  $p_T$ . The effect would cancel if integrated over  $2\pi$  in  $p_T^{\parallel}$ . One has to note that only the charged fraction of  $p_T$  in our estimate would contribute to the missing  $p_T^{\parallel}$  measurement. On a qualitative level, the effect of multiple independent jet production will contribute to the  $p_T^{\parallel}$  in- and out-of-cone measurements and should be taken properly into account when interpreting the experimental results. More quantitative estimates would involve more realistic simulations, addressing the  $A_J$  bias, and ultimately require assumptions about the underlying partonic energy loss mechanism.

#### IV. EFFECT ON $A_J$

Taking contributions of jet  $v_3$  and multiple jet production on the di-jet balance  $A_J$  into account, the observed, leading jet energy can be expressed as

$$E_1 = \tilde{E}_1 + E_{v_3} + E_{nth}, \quad (4)$$

with  $\tilde{E}_1$  the leading jet energy,  $E_{v_3}$  the contribution from jet  $v_3$  and  $E_{nth}$  the energy of  $n^{\text{th}}$  hard scatterings overlapping with the leading jet. Similarly the sub-leading, di-jet partner jet energy can be expressed as

$$E_2 = \tilde{E}_2 - E_{v_3}. \quad (5)$$

Therefore, the di-jet imbalance  $A_J$  can be written as

$$A_J = \frac{E_1 - E_2}{E_1 + E_2} = \tilde{A}_J + \frac{2E_{v_3} + E_{nth}}{E_1 + E_2}, \quad (6)$$

where  $A_J$  is the imbalance of the true di-jet pair ( $\tilde{A}_J$ ) with a positive contribution of twice the energy caused by jet  $v_3$  and the contribution from multiple hard scatterings. For a recent calculation of  $\tilde{A}_J$  including NLO effects, we refer to [25]. We would like to point out that estimating the additional effects on  $A_J$  without a realistic simulation is complicated by the experimentally used

background subtraction scheme. If the  $n^{\text{th}}$  hard scatterings in a certain kinematical region, as expected from binary scaling, are abundantly produced in the experimental phase space, then part of their effect should be accounted for in the background correction.

Overall, the discussed effects will lead to an increase in  $A_J$ , but further, more detailed, studies would be needed to quantitatively estimate their contribution on the measured  $A_J$  distribution.

#### V. SUMMARY

Recent jet quenching measurements in Pb+Pb collisions at the LHC report a significant energy imbalance of di-jets[12, 13]. The imbalance is found to be compensated by a large amount of soft particles produced at large angles with respect to the di-jet axis [13]. We qualitatively discuss two effects of the underlying heavy-ion background, jet  $v_3$  and multiple jet production.

The effect of jet  $v_3$  on  $p_T^{\parallel}$  out-of-cone in our simplistic approach suggests a moderate, but finite contribution of a few GeV/c for realistic bulk  $v_3$  values and large jet  $v_3$ .

The influence of multiple di-jet production per event, for  $\hat{p}_T$  values of the order of the effect (10 GeV/c), can contribute significantly in the  $p_T^{\parallel}$  in- and out-of-cone measurements provided it is caused by a centrality dependent, bias towards events, in which the 2<sup>nd</sup> hard jet is in the vicinity of the selected leading jet. In addition, due to the hard cutoff imposed on the leading jet energy, the fraction of these events should be enhanced due to a feed-up of lower energetic jets in the measured di-jet selection.

We want to emphasize that the  $p_T^{\parallel}$  measurement over  $2\pi$  [13], independent on the details of the composition of the leading jet selection and bulk-like correlation effects, is a clear indication of partonic energy loss in heavy-ion collisions at the LHC, in which high- $p_T$  suppression is balanced by an enhanced production of low- $p_T$  particles. However, we think that the discussed effects should be taken into account, and further quantified, in order to unambiguously conclude whether the quenched energy appears at large angles with respect to the jet axis.

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